MASSACHUSETTS INSTITUTE OF TECHNOLOGY
HAYSTACK OBSERVATORY
WESTFORD, MASSACHUSETTS 01886

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Telephone: 617-715-5533
Fax: 781-981-0590

To: EDGES Group

From: Alan E.E. Rogers and John Barrett

Subject: Measurements of the galvanized ground plane mesh permeability and ground plane loss estimate

Two 12 inch long samples of the galvanized carbon steel 3.075 mm diameter rods were made into 50 ohm transmission lines using brass tubes with 0.277 inch inner diameter and soldering female SMA connectors on each end as shown in Figure 1. One of the transmission lines had the very thin zinc coating removed for a comparison. The rods were checked and were found to be attracted to a magnet as expected for carbon steel. The measured DC resistance of the rods was 7.2e-3 ohms consistent with the conductivity of carbon steel of 7e6 S/m.

The following VNA measurements using calibration Short, Open, Load were made:

SOL on the VNA , SOL on the end of the T-line without galvanized coating, SOL on the end of T-line with galvanized coating. SOL on T-lines repeated reversing ends of the T-line for a total of 15 measurements covering 50 to 200 MHz in 1 MHz steps.

The S-parameters from the calibrated one port s11 were derived for each T-line. The T-line impedance etc. at 75 MHz are listed in Table 1.

T-line	S11 dB	S1221 dB	SR1221 dB	S22 dB
Galvanized	-28.5	-0.082	-0.084	-28.5
Not Galvanized	-31.2	-0.122	-0.122	-31.2

Table 1. S-parameter amplitudes at 75 MHz as an example

The S12 amplitude and phase is plotted in Figure 2 along with cable simulations using transmission line theory of S. Ramo and J. B. Whinnery, Fields and Waves in Modern Radio with the inclusion of the permeability along with the conductivity. The best fit values obtained for permeability are 16 and 42 for the galvanized and the non galvanized lines respectively and are plotted as the thin lines which lie almost on top of the thick lines of the measured data. The permeability of 42 is close to the nominal 50 expected for carbon steel. If the zinc coating was thicker than the skin depth of about 20 microns the S12 would be -0.02 dB at 75 MHz or a factor of about 4 better. The plots for the reversed direction are almost identical as they should be within the measurement noise for a passive network – see memo 130. The poor performance is not unexpected as the galvanization is intended for prevent corrosion and there are no specifications for the use of galvanized steel welded mesh for shielding.

The effect of an inadequate galvanized plating of the mesh on the ground plane loss has been studied in memos 316, 327 and 328. Note that in these memos a conductivity of 1e06 S/m was assumed for the steel which is lower than the measured value of the sample. Even with the high loss the total loss is still under 0.5% but the frequency dependence below 75 MHz results in 10 mK level with 5-terms removed at GHA = 12 hours. But corrections may be required to reach the level needed for extraction of the absorption within a few hours of the transit of the galactic center.

Table 2 shows the results of a check using FEKO to model the shorted T-line using the measured dimensions and the permeability from the transmission line model. In both cases a conductivity of 7e6 S/m was used.

T-line	Measured 50 MHz dB	100 MHz dB	FEKO 50 MHz	100 MHz	perm
Galvanized	-0.27	-0.32	-0.22	-0.26	16
not Galvanized	-0.39	-0.49	-0.36	-0.41	42

Table 2. Measured S11 with T-line shorted compared with FEKO T-line model with best fit permeability from transmission line model

Even though the mesh loss is a small fraction of a percent there are conditions when it only requires a loss of 0.01 percent with a resonance or poor ground shielding with rock below as discussed in memo 283 to produce a sufficient lack of a smooth frequency dependence to mimic a 21-cm absorption. However these effects will scale with sky noise levels and cannot explain the variations of residuals which change rapidly with GHA like those due to scattering as in memo 348. The most critical is the mesh attached to the aluminum center plate which is studied in memo 328. The results of FEKO estimates for the resistive loss using mesh attached to each side of the aluminum center plate described in memo 328 are given in Table 3. These resistive loss percentages should be approximately doubled when the mesh is extended to form a 30x30m ground plane as discussed in memo 328.

mesh permeability	free space 50 MHz	with soil 50 MHz	free space 100 MHz	
16	0.032	0.025	0.018	4-sides
42	0.052	0.04	0.030	4-sides
16	0.07	0.05	0.04	rough estimate
42	0.10	0.08	0.06	all ground plane

Table 3. Estimated resistive loss in percent from the mesh on 4-sides of the aluminum center plate.

The loss in the mesh with soil of dielectric 3.5 and conductivity 1e-3 S/m is a little lower because the presence of the soil suppresses the reflection from the edges of the mesh. Resonant effects are also suppressed by the soil. The effects of rock layers below the soil are studied in memo 283 show that poor connections between the mesh and the center plate can result in a loss of shielding factor which can result in artifacts as pointed out by Bradley et al. 2019 ApJ 874,153 and is discussed memo 309.

An estimate of shielding loss was made in memo 315 of about 0.1 percent which places the upper limit on shielding and resistive loss using permeability of 16 of 0.06 percent for a ground plane of 30x30m or larger. There are 3 basic sources of loss

a) “resistive” loss in the antenna and ground plane
b) loss which results from the “shielding” of the mesh which allows some power from the antenna beam to leak through the mesh into the ground
c) loss from “spillover” of the antenna beam onto the ground outside the ground plane

It is difficult to estimate the shielding and spillover loss because a large structure is needed which requires very large amount of compute time. In practice the estimates of the separate loss terms can only be obtained by using the scale factors and special tests. For example the spillover at a fixed frequency scales inversely with ground plane linear size squared and close to being constant for a ground plane linear size in wavelengths. The shielding loss due to leakage scales with mesh wire spacing squared from memos 88 and 316. The shielding loss frequency dependence is also is agreement with mesh shielding measurements of El-Maghrabi (2018).
The frequency dependence of the loss is approximately given by

$$loss = R(f^{0.5}) + S(f^2)(m^2) + Sp(f^{-2})(L^{-2})$$

where R is the resistive loss factor
S is the shielding loss factor
Sp is the spillover loss factor
L is the normalized linear size of the ground plane
m is the normalized mesh wire spacing
f = is the normalized frequency

For frequency normalized to 50 MHz, m = 5 cm, L= 30m, R ~0.03, S ~0.05 and Sp ~0.2 percent. The resistance factor is for the galvanized mesh with permeability of 16 which increases to R ~0.15 for a permeability of 42. These factors are derived primarily from the geometry of figure 2 in memo 328 which was run with soil dielectric of 3.5 and different mesh permeability and wire spacing using method of memo 258. Figure 3 shows a FEKO estimate of the loss for a solid center plate extended to 5x5m with 20cm mesh. Resistive loss was not included and a larger wire spacing was used to get an estimate of the shielding loss.

Table 4 summarizes the losses for EDGES antennas and ground planes

Loss source	antenna	Ground plane	Frequency MHz	Loss %	memo
antenna resistive	EDGES-3	all	50	0.15	329
balun tubes	midband	all	50	0.22	329
balun tubes	lowband	all	50	0.035	329
shielding + spill	all	30x30m	50	0.5	
spillover	all	5x5 plus	65	1.4	290
mesh resist + shield	all	all	50	0.08	

Table 4. Losses for some specific cases

In summary the effects of resistive loss in the ground plane mesh are expected to be less than 0.1 percent with frequency structure under 10 mK for 5-terms removed from 50 – 100 MHz provided the sample is representative of the mesh delivered to the MRO for the 48x48m ground plane.

Ref. El-Maghrabi, Hany M. "Electromagnetic Shielding Effectiveness Calculation for Cascaded Wire-Mesh Screens with Glass Substrate." Applied Computational Electromagnetics Society Journal 33, no. 6 (2018).

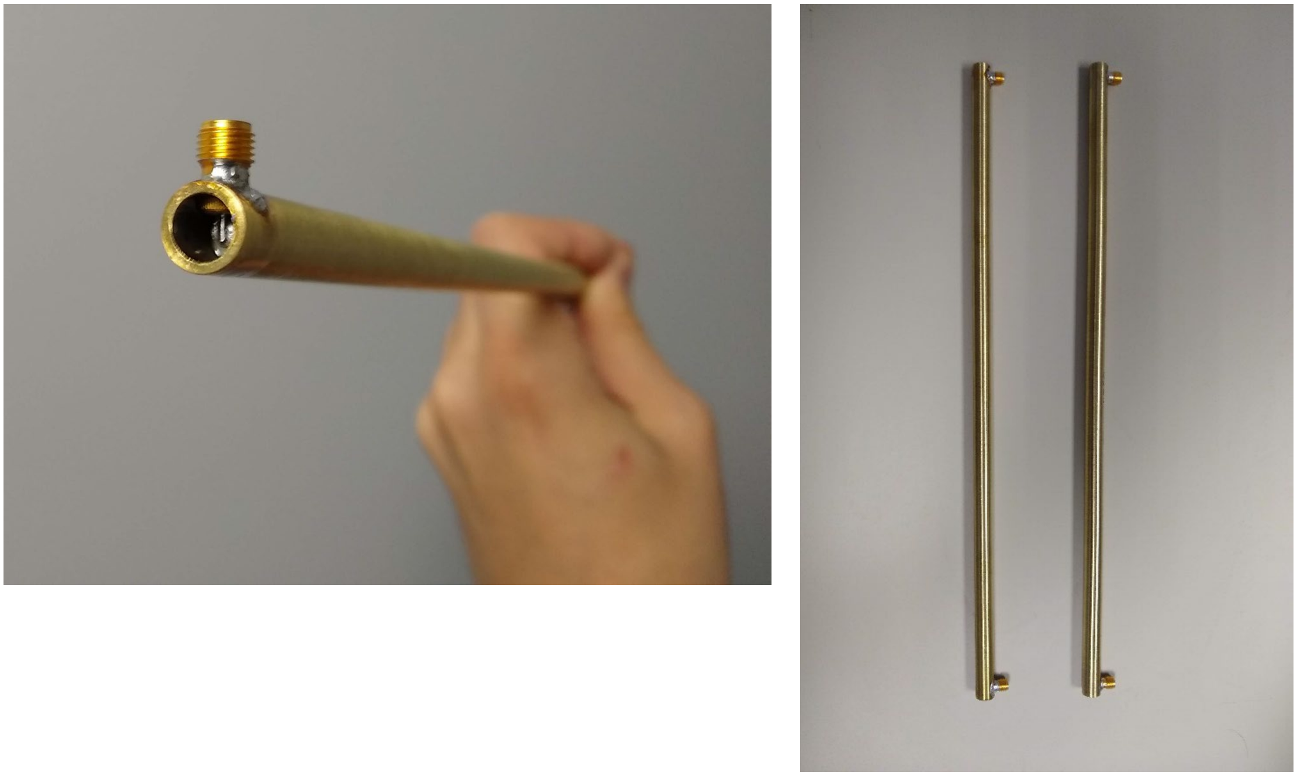

Figure 1. Photos of the transmission lines

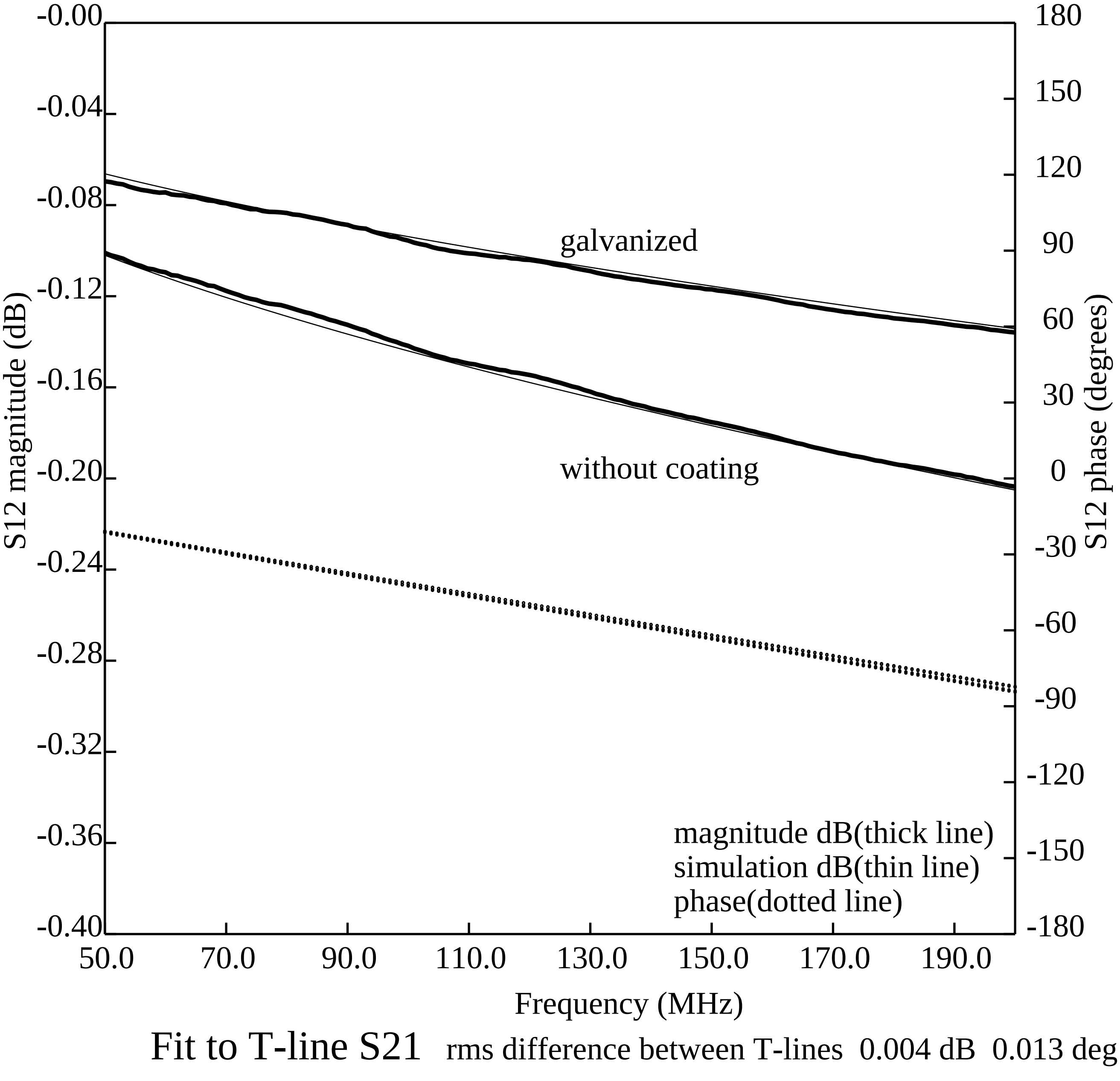

Figure 2. Plot of the transmission lines loss and phase along with plots for the best fit transmission line models with permeability values of 16 and 42 for the galvanized and with zinc layer removed respectively

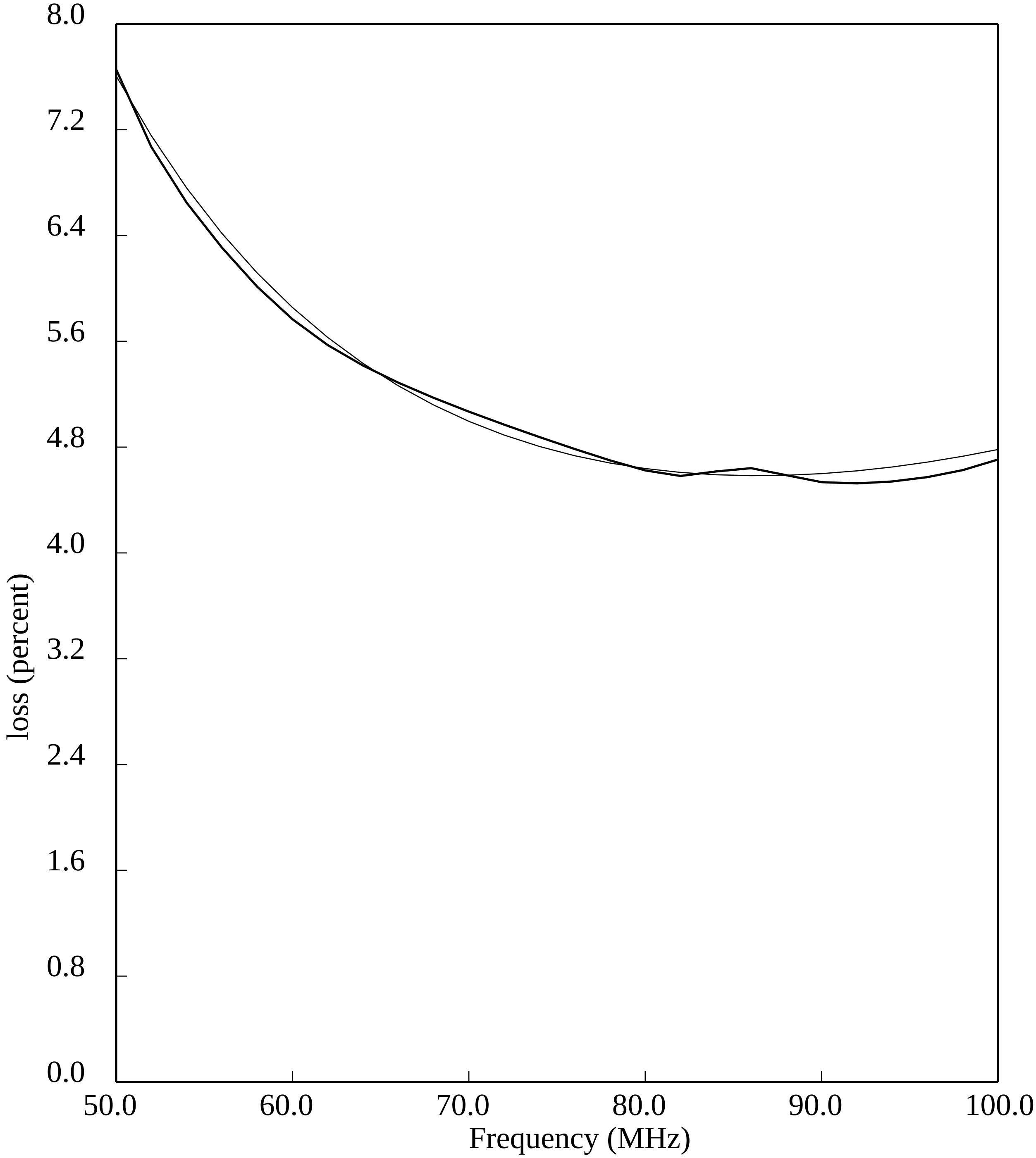

Figure 3. Plot of loss for 5x5m ground plane with solid plate under antenna and 20x20cm mesh along with fit using parameters of 0.0,0.048 and 0.19 for resistive, shielding and spillover.

ADDENDUM

Notes on measurements of transmission line samples of EDGES-3 ground plane mesh.

DC resistance:

Due to the the low resistance of the short transmission line samples a crude 4-point measurement was done using a DMM, low-voltage power supply, 15 ohm wire wound resistor, and the transmission line under test. The resistance of the 15 ohm resistor taken with a M210 RhoPoint milli-ohmeter and was found to be 14.96 ohms. The transmission line was then shorted at one end while the other end was connected in series through the 15 ohm resistor to the power supply via a SMA-BNC adapter. A current was then fed through the resistor/shorted-transmission line circuit and the Fluke DMM was use to measure the voltage differences. A table summarizing the measured values is below. V_r is the voltage across the load resistor, V_o is the voltage across the outer conductor between points A and B (just below the center of each SMA connector), while V_i is the voltage across the inner conductor between points C and B (the exposed inner conductor, shown in figure below), I is the inferred current while R_o and R_i are the inferred resistances of the outer and inner conductors.

Sample	V_r (V)	V_o (mV)	V_i (mV)	I (mA)	R_o (ohm)	R_i (ohm)
ungalvanized	13.87	0.5	6.7	927	0.00054	0.0072
ungalvanized	10.42	0.4	5.0	696	0.00057	0.0072
ungalvanized	5.153	0.2	2.5	344	0.00058	0.0073
galvanized	13.88	0.5	6.7	927	0.00054	0.0072
galvanized	10.07	0.4	4.8	673	0.00059	0.0071
galvanized	5.134	0.2	2.4	343	0.00058	0.0070

The average resistances of the outer and inner conductors for the ungalvanized transmission line sample were 0.56 and 7.2 milliohms respectively, while for the galvanized sample the average resistance of the outer and inner conductors were 0.57 and 7.1 milliohms.

VNA Measurements:

The RF properties of the two transmission line samples were measured using a Keysight N5222A PNA. The power level was set to 0 dBm and the female Keysight cal-kit (85033D/E) was added to the VNA via the entry-wizard in order to remove the PNA cable properties. The serial numbers of each cal-kit load are recorded below:

Male cal-kit serial numbers:
Short: 059654
Open: 060138
Load: 058508

Female cal-kit serial numbers:
Short: 059405
Open: 059193
Load: 061215

The PNA was configured to take data by averaging 32 measurements of 151 steps over the range of 50-200MHz, and the data file were saved as .s1p and .csv files. Then a series of one-port measurements were taken. The first three were of just the female cal-kit SOL, each attached to the PNA cable directly, with the files named as follows:

SHORT -- The female cal-kit short directly on VNA
OPEN -- The female cal-kit open directly on VNA
LOAD -- The female cal-kit load directly on VNA

This was followed by six measurements for each transmission line sample (ungalvanized, and galvanized). These six measurements consisted of two sets of three measurements (one set for each orientation of the transmission line) using the male cal-kit SOL attached to the far end of the transmission line.

The files associated with the galvanized center conductor transmission line were named as follows, where 'X' denotes a 0 or 1, which corresponds to which end of the transmission line was attached to the VNA.

GLINE_SHORTX -- The galvanized transmission line with the male cal-kit short.
GLINE_OPENX -- The galvanized transmission line with the male cal-kit open.
GLINE_LOADX -- The galvanized transmission line with the male cal-kit load
While the files associated with the stripped (ungalvanized) transmission line were named similarly (where 'X' denotes 0 or 1 which is the end that was attached to the VNA.

LINE_SHORTX -- The steel transmission line with the male cal-kit short.
LINE_OPENX -- The steel transmission line with the male cal-kit open.
LINE_LOADX -- The steel transmission line with the male cal-kit load.